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Agro-economic prospects for expanding soybean production beyond its current northerly limit in Europe

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ABSTRACT

Soybean is one of the five crops that dominate global agriculture, along with maize, wheat, cotton and rice. In Europe, soybean still plays a minor role and is cultivated mainly in the South and East. Very little is known about the potential for soybean in higher latitudes with relatively cool conditions. To investigate the agronomic potential and limitations of soybean for feed (high grain yield) and food (high protein content, e.g., for tofu production) in higher latitudes, an organic soybean cropping system experiment was carried out from 2015 to 2017 in northeastern Germany. The objectives were: (1) to identify food- and feed-grade soybean cultivars that are adapted to a central European climate in terms of protein, grain yield, and yield stability, (2) to explore the effect of irrigation on soybean protein and grain yield under relatively dry growing conditions, and (3) to determine the agro-economic potential of soybean cultivation for both feed and food markets. Three soybean cultivars were tested with and without irrigation. The soybean feed-grade cultivars 'Sultana' and 'Merlin' were better adapted to the growing cycle and temperature, providing higher and more stable yields (average 2700 kg ha^{-1}) than the food-grade cultivar 'Protibus' (average 1300 kg ha^{-1}). Irrigation increased soybean grain yields by 41% on average. In the year with sufficient precipitation, no additional irrigation was necessary. Gross margins of organic soybean ranged between 750 € ha^{-1} for the rainfed food-grade soybean and 2000 € ha^{-1} for the irrigated feed-grade soybean and were higher than other crops. We demonstrated a large agro-economic potential for soybean as a novel grain legume crop to diversify cropping systems and increase the production of protein crops in central Europe.

1. Introduction

Due to its high protein content and ideal amino acid composition, soybean (*Glycine max* (L.) Merr.) is considered as an excellent feed supplement, particularly for monogastric animals (Montoya et al., 2017), and has become one of the most important commodities in global trade (Sun et al., 2018). World production increased from approximately 160 million tonnes on 70 million ha in 1998–350 million tons on 125 million ha in 2018 (FAOStat, 2021), with 92% of the production in the USA, Argentina, Brazil, China and India (Pagano and Miransari, 2016). The area of organically managed soybean is still small but has doubled in three years to about 560,000 ha (fibl.statistics, 2020) or 0.5% of the total soybean area.

The European Union imported an annual average of 14 million tonnes of soybeans and 18 million tonnes of soybean cake in the five years to 2019 (EUROStat, 2021), of which all but 2 million tonnes came from other continents (FAOStat, 2021). At the same time, the EU grew 2.7 million tonnes of soybean while non-EU European countries produced another 8.4 million tonnes (EUROStat, 2021; FAOStat, 2021). Hence, there are many market opportunities for soybeans in Europe (Sibert and Tränkner-Benslimane, 2020) and the production for high-value sectors such as food-grade or organic can be very profitable (Cox et al., 2019). The high demand for soybean protein in Europe is therefore an important reason for expanding soybean cultivation to

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central and northern growing areas where it is a minor crop, e.g. with only 33 thousand hectares in Germany in 2020 compared to 2.7 million hectares of maize (destatis, 2021). European self-sufficiency in soybean would require 9 – 12% of its arable land to be sown to this crop (Guilpart et al., 2020).

Gross margin and its stability are often the deciding factor as to whether a farmer grows a particular crop. The published studies on gross margins of soybean compared to other main cultivated crops in central Europe (e.g., Schätzl et al. (2019) and Reckling et al. (2020) for Germany) do not unravel the management factors leading to high or low gross margins.

Many see a need to diversify cropping systems in Europe where they are currently dominated by cereals and oilseed rape (Hufnagel et al., 2020). Recent studies have addressed different aspects of soybean cultivation in Europe, including predicting soybean phenology (Schoving et al., 2020), simulating emergence and germination (Lamichhane et al., 2020), summarizing current soybean production potentials and challenges in Switzerland (Klaiss et al., 2020), identifying the cropping potential of soybean above its current northern limit in Europe (Toleikiene et al., 2021) and in a co-design approach with farmers (Reckling et al., 2020).

The climatic conditions for soybean cultivation in central and northern Europe are similar to those in other "northern" soybean producing countries such as the southern parts of the Canadian prairies. The limiting factors are cultivar-specific daylength requirements for flowering, along with temperature and rainfall, mainly at the time of germination and flowering (Gawęda et al., 2020; Mandić et al., 2017). Soybean requires a sufficient number of warm days to mature, quantified by the growing degree days (GDD). Kühling et al. (2018) reported 933–1041 GDD (10 °C base) for a site in northwest Germany (52.32° N 8.04° E) as sufficient. The crop requires a soil temperature of 8 – 12 °C for germination, with lower temperatures reducing plant density and yield (Yamaguchi et al., 2014). Soybean is also sensitive to cold at flowering (Balko et al., 2014) with temperatures below 8 °C associated with poor fertilization of ovules and subsequent blossom dropping (Yamaguchi et al., 2014).

An adequate water supply is critical for crop growth and yield formation (Aydinsakir, 2018). Drought stress at germination or flowering causes similar effects to cold stress, although drought in the early stages of crop development has been reported to have no major growth-limiting consequences (Montoya et al., 2017). In areas with dry summers and sandy soils, irrigation may be considered (Aydinsakir, 2018), but there is little published evidence as to whether irrigation is economical for soybean production in temperate climates (Butz, 2016; Ziolkowska, 2015).

Hence, there is still little knowledge about the yield potential of soybean under central European conditions, the suitability of available cultivars, the value of irrigation and the economic impact. We established a multi-year experiment with the aim of determining the productivity, stability, irrigation requirements and profitability of typical soybean cultivars in northern Germany, with the following objectives: (1) to identify food- and feed-grade soybean cultivars that are adapted to a central European climate in terms of protein, grain yield, and yield stability, (2) to explore the effect of irrigation on soybean protein and grain yield under relatively dry growing conditions, and (3) to determine the agro-economic potential of soybean cultivation for both feed and food markets.

2. Methods

2.1. Experimental site

The field trial was conducted at the experimental station of the Leibniz Centre for Agricultural Landscape Research (ZALF) in Müncheberg (52°31′N, 14°07′E, 62 m above mean sea level), 50 km east of Berlin, in 2015–2018. Detailed data on soils, weather, crop and management parameters are provided in the data set https://www.doi.org/10.4228/ZALF.DK.103 (Reckling and Rosner, 2020). Soils at the research station are from glacial deposits and are predominantly sandy loams and loamy sands with a high spatial heterogeneity containing on average 61% sand, 27% silt and 12% clay. The soil pH (KCl) ranges between 6.1 and 6.9, total soil carbon between 0.4% and 0.7% and the plant-available water-holding capacity is estimated as a maximum of 150 mm in the rooting zone of 1 m. The long-term average annual temperature is 9.0 °C with an average annual precipitation of 563 mm.

2.2. Experimental design

The experiment was a two-factor split-plot design with six replicates. The main-plot factor was the three soybean cultivars, 'Protibus' for food and 'Sultana' and 'Merlin' for animal feed. The subplot factor was the water supply, rainfed and irrigation. In each preceding year, the experimental area was cropped with maize (*Zea mays* (L.)).

Procedures and dates for sowing, crop management and harvesting were similar in all three years (Table 1). Soybeans were sown between 2 and 18 May in rows spaced 50 cm apart with a sowing density of 70–80 viable grains per m^2 and a depth of 3–4 cm. Mechanical weed control was performed with harrowing before and after emergence and twice per year using a mechanical hoe between the rows. No plant protection chemistry or fertilizer, conventional or organic, was used.

From the start of flowering at the beginning of July, water was supplied to the irrigated subplots ten times in 2015 (with a total of 165 mm in July - September, with 10 – 25 mm per day), five times in 2016 (87.5 mm in July only, with 5 – 25 mm per day) and zero times in 2017 because of sufficient and well distributed rainfall. The amount of irrigation was determined by the WEB-BEREST model that calculates the irrigation water based on the crop demand using the coefficient of actual to potential evapotranspiration (Mirschel et al., 2020). The dates, applied irrigation amounts, precipitation, temperature, radiation and potential evapotranspiration calculated according to Wendling et al. (1991) are provided in the data set by Reckling and Rosner (2020).

2.3. Crop and soil sampling

Soybeans were harvested with a plot-harvester between mid-September and mid-October depending on the year (Table 1). In 2015, cv. 'Protibus' was harvested by hand because the plants were not sufficiently matured for the machine harvester. Grain moisture was determined by drying a defined quantity of grain for 2 h at 120 °C, calculating the moisture content and using it to adjust the grain yield (kg ha^{-1}) to 14% moisture content, crude protein content (%) and crude protein yield (kg ha^{-1}) to 100% dry matter content. Grain protein content (N x

Table 1
Key dates and agrotechnical practices for soybean cultivation conducted in 2015–2017.

Activities/ observations	2015	2016	2017
Soil preparation	13.4.	18.9.	–
		2.10.	–
Ploughing	14.4.	8.4.	16.3.
Sowing	18.5.	9.5.	2.5.
Emergence	28.5.	20.5.	15.5.
Mechanical hoeing	12.6.	31.5.	23.5.
	30.6.	6.6.	8.6.
		24.6.	16.6.
Manual hoeing		21.–23.06.	03.–06.06.
Start irrigation	3.7.	4.7.	–
Harvest	5.10. ('Sultana','Merlin') 23.10. (Protibus)	15.9.	17.10.
Soil samples	24.10.	20.11.	21.11.

6.25) (the common conversion factor for legumes, although it is currently critically discussed as not ideal in all cases (Mariotti et al., 2008)) was determined by the central laboratory at ZALF using Kjehldahl digestion and photometric determination (AAS-iCE 3300, Gallery™ Plus, ThermoFisher Scientific GmbH Microgenics GmbH, Hennigsdorf, Germany).

2.4. Economic assessment

A gross margin calculator was used to calculate the revenues, variable costs and the gross margin (LfL, 2020) of soybean (organic for feed and food) and for comparison of winter wheat (*Triticum aestivum* (L)) (feed and food) and narrow-leafed lupin (*Lupinus angustifolius* (L.))(feed and food). Wheat as a comparison with grain and lupin to compare the gross margins of another legume with soy.

In this online tool, the revenues for soybean, winter wheat and narrow-leafed lupin were calculated on the basis of the yields and producer prices. Variable costs were calculated as the sum of the costs for seed, inputs, hail insurance, cover crops, cleaning, irrigation, drying and variable machinery. These variable costs were subtracted from the revenues to calculate the gross margins.

The average grain yields of soybean from 2015 to 2017 were used to calculate the gross margin. Feed-grade soybean was represented by cv. 'Sultana' and food-grade soybean by cv. 'Protibus'. The yields for lupin, oat and wheat were obtained from the organic monitoring plots at the same research station with similar soil and management conditions and over the same period. The gross margins of the irrigated systems were calculated for 2015 and 2016 (no irrigation in 2017). The average costs of irrigation were estimated as 1.34 € mm^{-1} ha^{-1} water.

2.5. Data analysis

JMP® version 4.3 (SAS Institute Inc., Cary, NC, USA) was used for the statistical analysis of the results. The Shapiro-Wilk test was conducted for determining normality of distribution (Shapiro and Wilk, 1965), while Levene's test was used for determining the homoscedasticity (Levene, 1960). Separately under rainfed and irrigated conditions, two-way analysis of variance (ANOVA) was performed to analyse the main effects of soybean cultivar and year as well as their interaction effect on soybean grain yield, crude protein yield and crude protein content. Soybean cultivar included three levels ('Protibus', 'Sultana'and 'Merlin') and year consisted of three levels (2015, 2016 and 2017). Additionally, the main effect of irrigation (water supply) and its interactions with cultivar and year were analysed using three-way ANOVA test on all three cultivars, years 2015 and 2016, and both irrigation treatments.

Means were compared with the Tukey post hoc (HSD) test with $P < 0.05$. For statistical analysis of the soil mineral nitrogen content, the sum of nitrogen from 0 to 90 cm was considered.

The model for three-way ANOVA was:

$$\boldsymbol{Y_{ijkl} = \mu + \alpha_i + \beta_j + \gamma_k + \alpha\beta_{ij} + \alpha\gamma_{ik} + \beta\gamma_{jk} + \alpha\beta\gamma_{ijk} + \delta_l + E_{il} + \tau_{jl} + \rho_{ikl} + e_{ijkl}}$$

and the model for two-way ANOVA was:

$$\boldsymbol{Y_{ikl} = \mu + \alpha_i + \gamma_k + \alpha\gamma_{ik} + \delta_l + E_{il} + \rho_{ikl} + e_{ikl}}$$

Where:

Y_{ijkl} and Y_{ikl} = responses (for all tested parameters)
μ = intercept (overall mean response of all observations)
a_i = the cultivar (fixed effect of whole-plot factor) of the i^{th} level of α
β_j = the irrigation effect (fixed effect of sub-plot factor) of the j^{th} level of β
γ_k = the year effect (fixed effect of sub-plot factor) of the k^{th}level of γ
$\alpha\beta_{ij}$ = interaction effect of cultivar by irrigation of the i^{th}level of α with the j^{th}level of β
$\alpha\gamma_{ik}$ = interaction effect of cultivar by year of the i^{th}level of α with the k^{th}level of γ
$\beta\gamma_{jk}$ = interaction effect of irrigation by year of the j^{th}level of β with the k^{th}level of γ
$\alpha\beta\gamma_{ijk}$ = interaction effect of cultivar, irrigation and year effect of the i^{th}level of α, the j^{th}level of β with the k^{th}level of γ
δ_l = the replicate effects (random effect)
E_{il} = the main-plot random error assumed independent and identically distributed (iid) N $(0,\sigma_\omega^2)$
τ_{ijl}= the interactions between irrigation and replicate nested by whole-plot cultivar (random effect)
ρ_{ikl}= the interactions between year and replicate nested by whole-plot cultivar (random effect)
e_{ijkl} and e_{ikl} = subplot error assumed iid N $(0,\sigma^2)$

Temporal yield stability was estimated for each cultivar separately with the *standard* coefficient of variation (CV; see Reckling et al. (2018) as:

$$CV = \frac{\widehat{\sigma}}{\widehat{\mu}} \bullet 100\%$$

where $\widehat{\mu}$ was the mean and $\widehat{\sigma}$ was the standard deviation of the grain yield across the years of the experiment. The CV was not adjusted following Döring and Reckling (2018) because the yield data were not sufficient to estimate *b* in Taylor's Power Law and because similar systems were compared. CV values could not be compared statistically because of the limited number of observations.The slope *b* of the regression of genotype against the mean yield in each environment was determined. This ecoregression coefficient *b* (Finlay and Wilkinson, 1963) is equal to 1 if there are no Genotype × Environment (G × E) interactions; $b > 1$ indicates that a tested genotype yields comparatively better in environments with a high yield potential, whereas $b < 1$ indicates relative yield advantages in environments with a lower yield potential. Ecovalence (Wricke, 1962) is the contribution of each genotype in all environments to the sum of squares of the G × E interaction. If ecovalence is small, agronomic stability is high.

2.6. Meteorological data

The average May to October air temperatures were 15.2 °C, 16.0 °C, 15.6 °C and 17.2 °C and total precipitation in the same period was 325 mm, 251 mm, 378 mm and 179 mm in 2015, 2016 and 2017, respectively.

In 2015, July and August were dryer than the long-term average, with a total rainfall of 66 mm compared to 123 mm (Fig. 1) and the temperature was very high in July with max. 35.3 °C and in August with max. 36.9 °C (Fig. 2). There were also two very cold nights (T ≤ 5 °C) in July and August, unlike in the other years of the experiment (Fig. 2A). In June 2016, rainfall was below average at 97 mm but was fairly evenly distributed (Fig. 1) and July was warmer than average (Fig. 1) with a maximum of 30.4 °C (Fig. 2). In 2017, there was an above-average amount of rain in June and July and temperatures were close to average (Fig. 1).

The growing degree days (GDD) were calculated using the standard formula (McMaster and Wilhelm, 1997):

$$GDD = \left[\frac{Tmin + Tmax}{2}\right] - T_{\text{Base}}$$

Where *Tmin* is the minimum temperature, *Tmax* is the maximum temperature and T_{Base} = 10 °C. GDD is the sum of all days from sowing to either the first day of frost (T < 0 °C) or harvest. In all three years of the

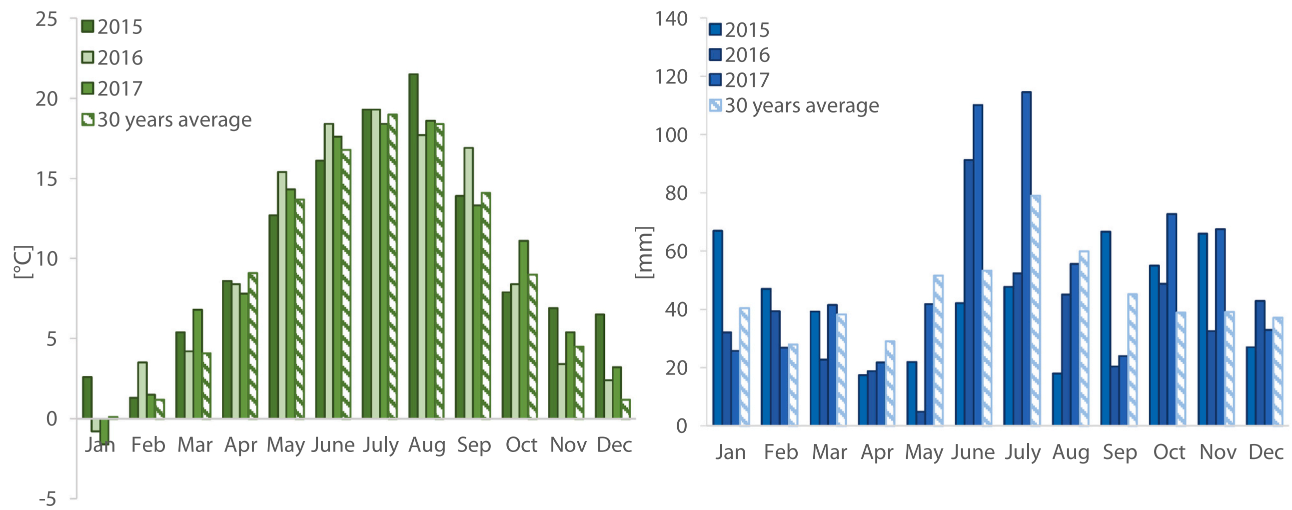

Fig. 1. Monthly total precipitation (mm) and monthly average temperature (°C) in Müncheberg in 2015–2017, compared with the 30-year average.

experiment, soybeans were harvested before the first day of frost.

3. Results

3.1. Soybean grain and protein yield

The growing seasons lasted 129 – 169 days, giving 969–1036 GDD (Fig. 2). Soybean grain yield ranged from approx. 1300 kg ha^{-1} to 3600 kg ha^{-1} (Table 2). Analysis of variance showed that soybean yield and soybean protein harvested per hectare were influenced by the main effects of two factors year and cultivar ($P < 0.01$) for both irrigated and rainfed plots. However, both these components of yield were unaffected by interaction of year with cultivar in irrigated plots; moreover, the interaction effect influenced the yield and content of protein harvested from the soybean in rainfed plots ($p < 0.05$). There was no significant difference between either the grain yields or the protein yields of cvs 'Sultana' and 'Merlin' (Table 2). Cultivar 'Sultana' yielded 79% and 108% more grain than cv 'Protibus' under irrigated and rainfed conditions, respectively (Table 2), and the protein yield of cv 'Sultana' also exceeded that of 'Protibus' by 32% and 66% in the same order.

Protein content was affected neither by year nor by its interaction with cultivar in the irrigated plots, but cultivar had a large effect ($p < 0.001$). In rainfed plots, the overall effects of the factors of year and cultivar on the content of protein in the soybean seeds were statistically significant (Table 2). The same was noted regarding the significance of the interactions between the two factors. In particular, cv 'Protibus' accumulated more protein in the seeds than either cvs 'Sultana' or 'Merlin', the difference being 6–7% points in irrigated plots and 3–4% points in rainfed conditions.

In general, supplementary irrigation significantly increased grain yield and protein yield by 40% and protein content by 5% (Table 3)).

Temporal yield variability under rainfed conditions was higher in 'Protibus' (CV 75%) than in 'Sultana' (CV 43%) and 'Merlin' (CV 45%) and in general, irrigation increased yield stability of all three cultivars by 7–11 CV percentage points (Table 2). The latter two cultivars were also better adapted to diverse environmental conditions and outperformed 'Protibus' under all conditions (Fig. 3). The ecoregression indicated that both 'Sultana' ($b = 0.75$) and 'Merlin' ($b = 0.86$) had a relative yield advantage compared to the mean of all varieties, especially in years with a lower yield potential. 'Protibus' ($b = 1.38$) performed slightly better in years with a high yield potential than in years with a low yield potential. At the same time, agronomic stability was larger for 'Merlin' and 'Sultana' than for 'Protibus' with ecovalence values of 26, 73 and 159, respectively.

3.2. Economic potential of soybean

With the average yields for the feed-grade soybean of 2800 kg ha^{-1} (represented by cv. 'Sultana' over the three years 2015–2017) and the variable costs of 948 € ha^{-1}, gross margins were 1423 € ha^{-1} (Fig. 4). Grain yields for the food-grade soybean (1700 kg ha^{-1} represented by cv. 'Protibus') were lower, variable costs were comparable with the feed-grade soybean and despite the 100 € higher prices, gross margins were lower than for the feed-grade soybean, at 751 € ha^{-1}. Higher gross margins were achieved for the irrigated systems in the dry years (2015–2016) with 2008 € ha^{-1} for feed and 1307 € ha^{-1} for food-grade soybean. With lupin yields in 2015–2017 of 2000 kg ha^{-1} and the relatively low prices compared to soybean of 530 € t^{-1} for feed and 720 € t^{-1} for food, the gross margins of lupin were 488 € ha^{-1} and 822 € ha^{-1}, respectively (Fig. 4).

Among the reference crops, winter wheat grown in the organic farming systems at the research station at ZALF (2015–2017), had the highest gross margins of 755 € ha^{-1} for food and 581 € ha^{-1} for feed (Fig. 4).

4. Discussion

These experiments were designed to test the potential to produce soybean in northern Germany and, by inference, in other central European regions with similar climates. The results showed that the gross margins were positive when the right cultivar was grown with the right management, although there were problems associated with the drought sensitivity of the crop and its susceptibility to cool temperatures during flowering.

4.1. Adaptation of soybean to a central European climate

The first factor limiting the expansion of soybean cultivation into cool-temperate climates is the temperature (Jähne et al., 2019; Kühling et al., 2018). During all three years of the soybean field trial, the earlier reported 933–1041 GDD (according to Kühling et al. (2018) for north-western Germany) was achieved (969, 1036, 992 GDD). The mean vegetation duration of the three years (143 days) was close to the average range (86–141 days) calculated from 20 different studies (Egli, 2011). However, there were occasions in all three growing seasons when temperatures dropped below the base temperature of 10 °C, at which growth is disturbed (Kumar et al., 2008; Miransari, 2015). Most critically, night temperatures fell below 5 °C during flowering in 2015 (Fig. 2), which is associated with flowers not being fertilized, dropping, and loss of yield (Borowska and Prusiński, 2021; Kurosaki and Yumoto,

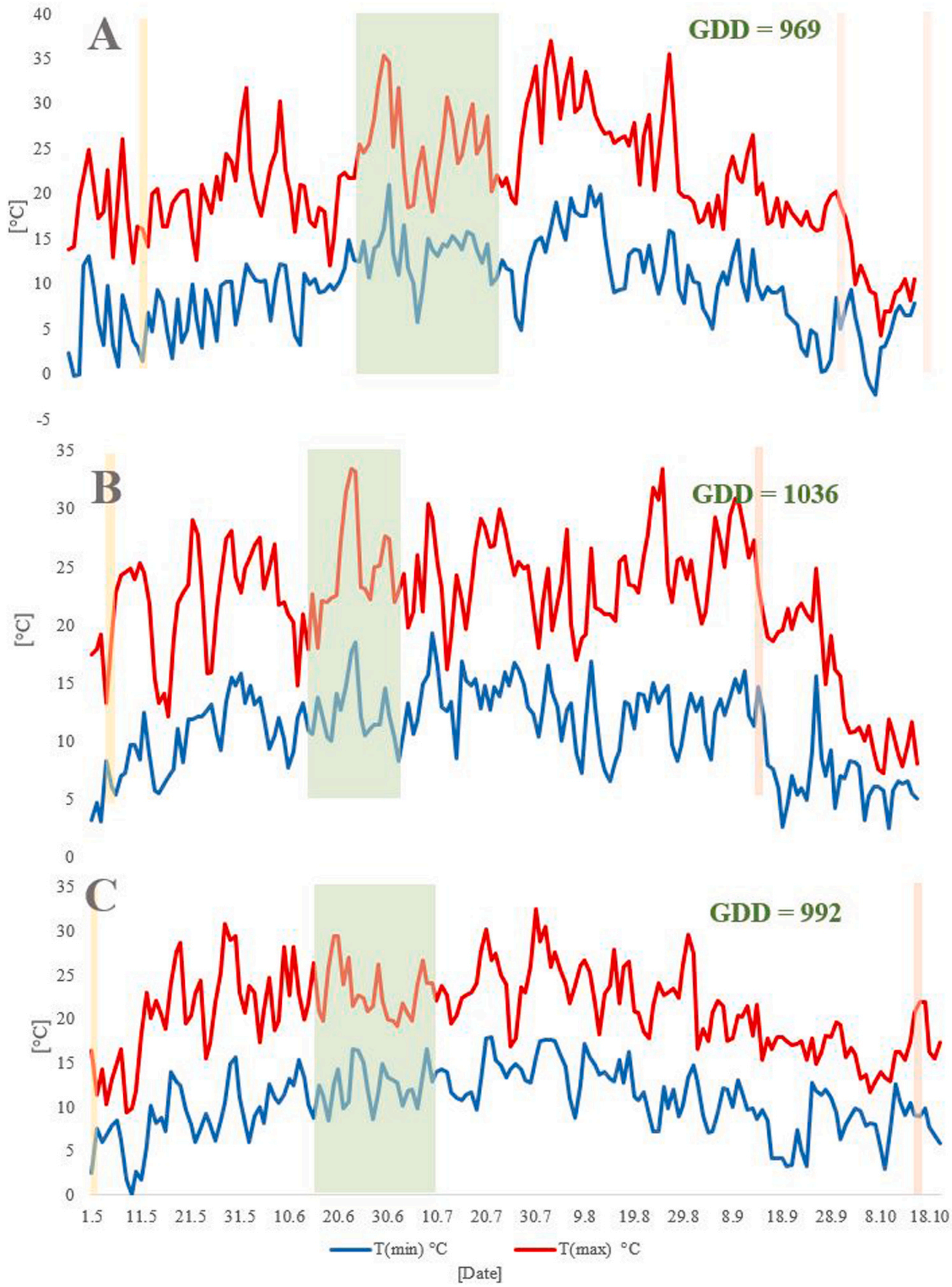

Fig. 2. Daily maximum and minimum temperatures (°C) from soybean sowing to harvesting in 2015 (A), 2016 (B) and 2017 (C). Colored areas: yellow = sowing; green = flowering; red = harvesting. In 2015, 1 Merlin and Sultana harvest, 2 Protibus harvest. GDD = growing degree days measured all over the vegetation period.

2003; Yamaguchi et al., 2014).

The date of sowing in 2015 was relatively late, owing to low soil temperature, and this may have contributed to the lateness of maturity of the crop in that year. Cool, damp conditions in autumn hinder ripening (Wilbois et al., 2014) and are typical of this region. Thus, it is necessary to select early-maturing cultivars for successful soybean production in central Europe (Balko et al., 2014). A recent field experiment showed that sowing date has a decisive influence on the nutrient contents of soybeans (Staniak et al., 2021). Early sowing in April increased crude fat, oleic acid and sucrose content in the seed, while later sowing in June led to higher protein and linoleic acid contents. This is also proved by Borowska and Prusiński (2021), accordingly, a late sowing also leads to a higher protein content, as this primarily depends on high temperatures and moderate precipitation during seed filling. However, delayed sowing leads to a significant decrease in yield (Serafin-Andrzejewska et al. (2021) .

A further limiting factor in soybean cultivation is water availability (Buezo et al., 2019; Jumrani and Bhatia, 2019). In central Europe June and July, when the soybean plants are flowering, are relatively dry. Water deficit or excess of water (Borowska and Prusiński, 2021) during flowering of soybean often leads to loss of flowers and low yield (Bernet et al., 2016; Karam et al., 2005). This also reflects the climatic water balance in these years in which the sum of precipitation during the vegetation period of the years 2015 and 2016 was much lower than 2017 (66 mm in 2015 and 97 mm and 2016, compared to 170 mm in 2017). In 2015 and 2016 precipitation was thus smaller than evaporation (Radzka et al., 2019), so in these two years irrigation was supplied.

Irrigation raised grain yield in both years that it was applied. Relief of water deficit in the flowering and grain filling phases of soybean results in improved photosynthetic performance (Frieler et al., 2017;

Table 2
Mean effects per year (2015–2017) and cultivar ('Merlin', 'Protibus', 'Sultana') effects of irrigated and rainfed soybean grain yield (kg ha^{-1}at 14% soil moisture), crude protein content (%), crude protein yield (kg ha^{-1} at 14% water moisture), along with yield stability of the cultivars (%).

Factors	Soybean (irrigated)				Soybean (rainfed)			
	Grain yield kg ha^{-1})	Crude protein content (%)	Crude protein yield (kg ha^{-1})	CV of yield (%)	Grain yield (kg ha^{-1})	Crude protein content (%)	Crude protein yield (kg ha^{-1})	CV of yield (%)
					Year			
2015	2133 b	43.7	782 b		913 b	43.5 a	331 b	
2016	3796 a	43.7	1543 a		2725 a	41.5 ab	1078 a	
2017					3090 a	39.3 b	1034 a	
					Cultivar			
'Merlin'	3621 a	41.3 b	1290 a	38	2652 a	40.0 b	898 a	45
'Protibus'	1854 b	47.5 a	949 b	68	1331 b	43.7 a	581 b	75
'Sultana'	3419 a	42.3 b	1249a	32	2745 a	40.6 b	965 a	43
					Significances			
Year	< 0.0001	0.9071	< 0.0001		< 0.0001	0.0008	< 0.0001	
Cultivar	< 0.0001	< 0.0001	0.0004		< 0.0001	0.0147	< 0.0001	
Year * Cultivar	0.4117	0.1259	0.5434		0.4675	0.0012	0.0171	

Significances as a result of two- way- ANOVA (Year * Cultivar). Different letters indicate significant differences between the means ($P < 0.05$) according to Tukey's test. Irrigation was not applied in 2017.

Wegerer et al., 2015), leading to higher biomass and grain yields (Di Mauro et al., 2019). A study by Borowska and Prusiński (2021) showed that average soybean yield decreases linearly with decreasing water availability, probably due to a considerable shortening of the vegetative and generative stages. A meta analysis of Rotundo and Westgate (2009) showed also that water stress reduces the protein and oil content of soybeans and confirms Borowska and Prusiński (2021) with the temperature dependence of the protein content. The meta analysis also confirmed, that the effect of waterstress is development dependent.

The yield benefit of irrigation in this region needs to be compared with its costs in terms of infrastructure and environmental impact in order to determine its long-term sustainability. Thus, the sustainability of irrigation is certainly also dependent on the amount of precipitation in the respective year and should be assessed accordingly.

The effect of water supply on protein content was inconsistent. Irrigation was associated with an increase in grain protein content in 2016 but not in 2015, and the grain protein content in the wettest season, 2017, was the lowest of the three years. Aydinsakir (2018) found that water deficit stress significantly decreased grain protein content of soybean in Turkey, but he also noted that there are opposite results about the effects of water deficit stress on soybean grain protein content in the literature, as this experiment confirms. Thus, the lower protein yields may also have resulted from a dilution effect due to the high rainfall in July 2017.

Table 3
Mean effect of irrigation (2015 and 2016) on soybean grain yield (kg ha^{-1}), crude protein concentration (%) and crude protein yield (kg ha^{-1}).

Factors	Soybean		
	Grain yield (kg ha^{-1})	Crude protein content (%)	Crude protein yield (kg ha^{-1})
		Irrigation	
Irrigated	2965 a	43.7 a	1165 a
Rainfed	1819 b	42.4 b	703 b
		Significances	
Year	< 0.0001	0.2443	< 0.0001
Irrigation	< 0.0001	0.0305	< 0.0001
Cultivar	< 0.0001	< 0.0001	0.0072
Year * Irrigation	0.7281	0.1151	0.8077
Year * Cultivar	0.0152	0.2245	0.5893
Irrigation * Cultivar	0.2198	0.5871	0.4821
Year * Irrigation * Cultivar	0.99	0.5198	0.9606

Significances as a result of three- way- ANOVA (Year * Irrigation * Cultivar). Different letters indicate significant differences between the means ($P < 0.05$) according to Tukey's test.

4.2. Cultivar differences

The cultivars 'Sultana' and 'Merlin' achieved similar yields and protein content in each environment, whereas 'Protibus' consistently produced the lowest yields (Table 2). 'Protibus' is known to react strongly and negatively to low temperatures, particularly during flowering (Schwärzel et al., 2016) as found in 2015 when its yield was lowest. The other two cultivars thus showed greater tolerance to cool weather. In a study by Staniak et al. (2021)yield differences between cultivars due to cold temperature conditions were also found and discussed in more detail. The loss of flowers by 'Protibus' in 2015 would have prolonged its reproductive growth in compensation, exposing it to cool, damp weather during the grain ripening phase, more than the other two cultivars, thus contributing to its poor harvestability in that year. Further contributions to the late maturity of 'Protibus' could include inoculation with rhizobia, since the better nitrogen supply can slow maturity and some cultivars are more sensitive to it than others (Kühling et al., 2018; Ray et al., 2006), along with the lateness of sowing in 2015.

Different measures of yield stability were calculated in order to assess different aspects of stability (Reckling et al., 2021). However, all three measures, relative yield stability, environmental adaptability and agronomic stability pointed in the same direction that the two cultivars 'Merlin' and 'Sultana' were more stable and adapted to a wider range of environmental conditions than 'Protibus'. A comparison of more cultivars and different environmental conditions in Central Europe is needed to identify traits affecting soybean yield stability under these conditions (Li et al., 2020).

'Protibus' was rich in crude protein, as expected, but its protein content fell in 2017. High protein contents are required in the production of soybean milk and tofu, the main products of food-grade soybean (Poysa et al., 2006), and the demand for locally produced soybean for tofu production is high in Europe (Kurasch et al., 2017). The analysis of the gross margins in this experiment showed that the higher price of 'Protibus' did not compensate for its lower yield, so we conclude that it is unsuitable for growing where there is a risk of cold temperatures during the summer and of a wet autumn. The two feed cultivars, 'Merlin' and 'Sultana', performed similarly to each other and better in most aspects than 'Protibus' so they can be considered suitable for the site if all conditions regarding climate and location are appropriate.

Ultimately, the choice of the right location and the right cultivar are the most important factors in soybean cultivation. The success of soybean cultivation in central Europe also depends primarily on weather conditions during all growth phases (Karam et al., 2005; Schori et al., 2005). The cultivar 'Merlin' may be more suitable for this region and

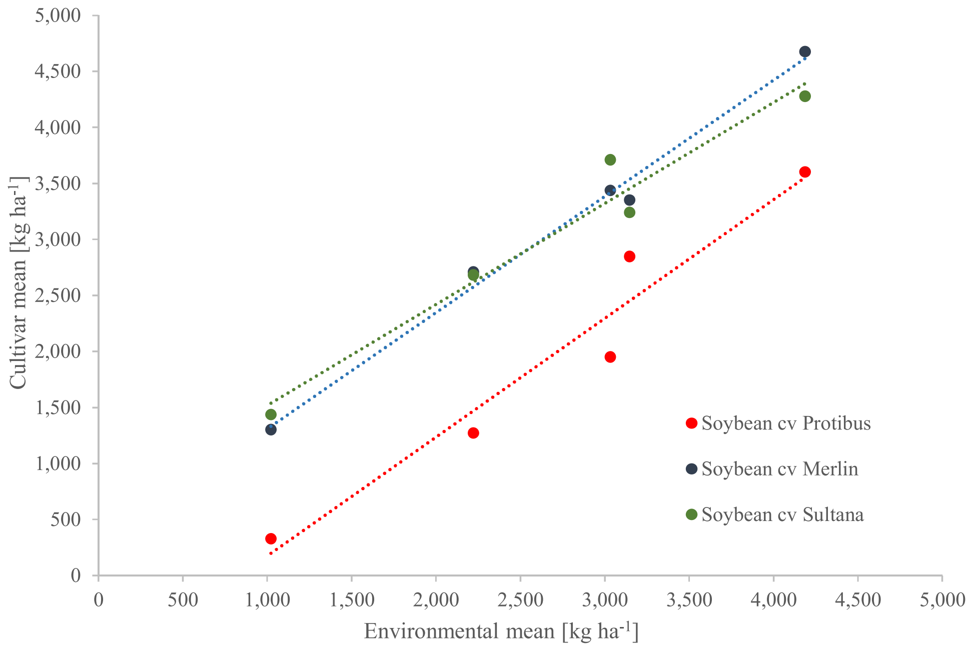

Fig. 3. Regression of mean cultivar grain yield (kg ha^{-1}) ('Sultana', 'Merlin', 'Protibus') on environmental mean (kg ha^{-1}).

very weedy fields due to its early maturity and fast early development according to the cultivar description, along with its slightly better ecoregression and ecovalence values shown here.

4.3. Agro-economic potential of soybean for feed and food markets

The expectation that the production of soybean would have a higher gross margin than those of wheatand lupin was confirmed.

The gross margins of irrigated soybean (feed) were 30% higher than those of rainfed soybean (Fig. 4). Based on this result, it can be seen that irrigation leading to an increase in yield is also reflected in an increased gross margin (when only the variable costs were included), especially in years with low precipitation. Halwani et al. (2019) indicated in a conventional soybean experiment at the same site that the higher revenues with irrigation compensated the irrigation costs. Irrigation on dry sites that have a high yield potential is especially relevant, since the yield gain covers the variable irrigation costs. Gross margins are strongly yield-dependent, and the yield, in turn, is very weather- and cultivar-dependent (Zarina et al., 2021).

The overall very high gross margins for organic soybean (Firgure 4) are mainly due to its high producer price, especially in comparison to the producer prices for organic lupin, attributable to the fact that the supply of local soybeans is still small and the demand is very high. The low yields and low producer prices for lupin led to its low gross margins (Carof et al., 2019; Preissel et al., 2015), but its positive pre-crop effect should be taken into account in the gross margin calculations. Many

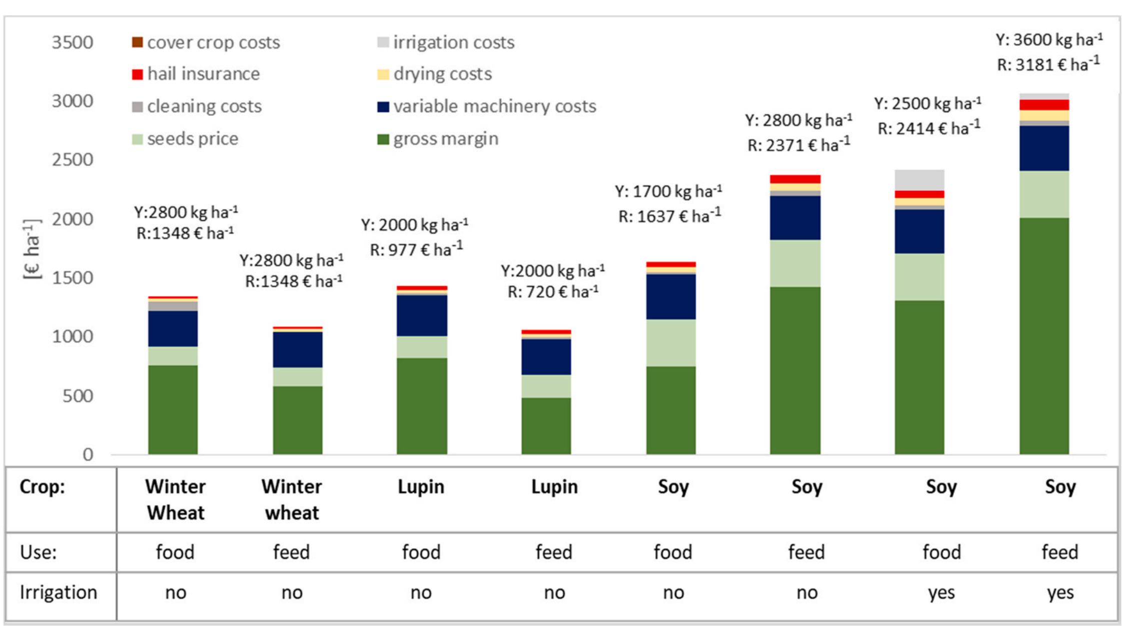

Fig. 4. Average gross margin and variable costs (€ ha^{-1} year $^{-1}$) of soybean (food and feed) with irrigation (yes;2015–2016) and without irrigation (no; 2015–2017), lupin (feed and food; 2015–2017) and winter wheat (2015–2017), with mean yields (Y) and and revenues (R) of the crops (above the bars) and mean variable costs of the respective years.

studies show that legumes as pre-crops in a cereal-dominated system increase the yields of the subsequent cereals but at present, there is little evidence for the pre-crop effect of soybean under European conditions (Preissel et al., 2015). In an experiment in Latvia, lupin achieved the higher gross margins compared to faba bean, pea and soybean (Zarina et al. (2021). In this experiment, soybean yields were extremely low (980-1440 kg ha^{-1}) compared to the other crops which could explain the relatively low gross margins. The study also found a strong dependence of the gross margin on the cultivar of the respective crop species.

5. Conclusion

Soybean cultivation is still very new in central and northern Europe so relatively little is known about its potential. This study showed that the tested food-grade cultivar achieved a high protein content, but because of its low yield and sensitivity to low temperatures, it cannot be identified as site-adapted. We also demonstrated a high agro-economic potential for the cultivation of early maturing soybean cultivars for feed use in a central European environment. The main finding was that soybean cultivation in these latitudes is highly dependent on temperature and the distribution of precipitation in the summer months of June to August. Cultivars adapted to these higher latitude conditions will have high potential to be used by farmers, when they are sown early, when they have rapid initial development, when they are tolerant against cold and drought spells in summer and when they mature in September or early October. In years with insufficient or poorly distributed rainfall, irrigation increases the grain yield and protein yield, which can compensate for the variable costs of irrigation but may not be sustainable depending on the source and availability of the water used. The gross margins for organic soybeans were very high in this study, as a result of high producer prices for GMO-free soybean from Europe.

CRediT authorship contribution statement

Kathleen Karges led the writing process and performed the data analyses together with Mosab Halwani. Moritz Reckling, Christine Watson, Frederick L. Stoddard, Sonoko Bellingrath-Kimura and Mosab Halwani contributed to the interpretation of the results and all authors were involved in the writing of the paper. Moritz Reckling designed and coordinated the experimental work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Competing financial interests

The authors declare no competing financial interests in relation to the work described.

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